AAMRL-TR-88-011

Aerospace Simulation 1988

ISBN 0-911801-28-6

Editor's Note: Normally papers were written after the authors have gotten at least some results to prove a point. Not so for the invited article below! In this case the authors are charged with managing a brand new concept, almost like a dream and turning it into reality some day. Here is how they describe their plans.

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Robotic telepresence: Applications of human controlled robots in Air Force maintenance

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ABSTRACT

This paper describes the major technology required to perform human-controlled robotic servicing of military aircraft during sortie regeneration in a chemical, radiological, or biological attack. Current and projected Air Force aircraft are designed to be serviced by human maintenance personnel. Wartime operations might make it desirable to remove these maintenance personnel from the hazardous flight line environment. Robots with human-like interface characteristics such as dexterous manipulators, vision, touch and hearing might be necessary to complete these tasks. The presentation will outline "Robotic Telepresence" as one solution to the complex requirement of rearming and servicing aircraft without exposing humans. The technology, when fully developed, will have maintenance personnel control robots that have quasi-anthropoid features from remote stations. Unique human capabilities are to be retained in the control loop while robotic ruggedness will be exploited. Research and development opportunities cross the traditional boundaries between hardware engineering and human factors applications. Unique challenges in this approach to integrate the human and the machine will be identified.

INTRODUCTION

Mission essential operations must be maintained in all military operational scenarios. Current operational capability is threatened by the degradation of flight line crew performance in Nuclear, Biological and/or Chemical (NBC) environments. These environments may lead to total crew incapacitation and total loss of mission capabilities. One potential concept for maintaining mission effectiveness in the NBC contaminated environment is Robotic Telepresence (R/T). This recently initiated concept would replace exposed maintenance personnel with robots that are under the direct, real-time control of remote human operators (Mohr, 1986). Robotic Telepresence would allow the operators to "see, feel and hear" the aircraft servicing environment through sensory systems on the robot. These human controlled robots could be used in various flight line aircraft servicing scenarios such as rearming weapons systems and refueling aircraft. Other applications include minor repair such as "black box" removal and replacement (Figure 1). Additional uses in tire and wheel changing and battle damage assessment may be developed. The concept integrates the human's ability to work in the unstructured flight line environment with the robot's ability to work in lethal environments contaminated by NBC weapons. Human-in-the-loop control of flight line robots may one day play a critical role in maintaining and enhancing mission

effectiveness in these environments by reducing human exposure and crew incapacitation in the NBC environments. In addition, a mature R/T technology might also achieve force multiplication via a one-to-many mapping between human operator and R/T robot.

MAINTENANCE ENVIRONMENT

Wartime aircraft maintenance operations may require personnel to perform servicing functions on flight lines that have been contaminated with disabling or lethal doses of NBC agents. These personnel must wear bulky protective garments that substantially reduce effective task performance by limiting or hindering communications, reducing fine manipulative dexterity, and decreasing operational time at the work site due to heat stress and fatigue factors. As a consequence, required aircraft servicing may be interrupted, delayed or even prevented by these factors.

Although the servicing tasks which must be performed in the NBC environments are practiced continually by maintenance crews, they are essentially unstructured. The servicing operations were designed to be completed by humans who can inspect, evaluate and manipulate objects within the environment. The work is unstructured in that placements of hardware are inexact, aircraft orientation and attitude may change during the loading/refueling operations and the precise operations to be completed will vary from aircraft to aircraft from day to day. Consequently, task completion places heavy emphasis on human recognition of the work site "as it is" before work is started, human understanding of the work site "as it should be at completion", human assessment of "what needs to be done" and appropriate real-time adjustments to successfully execute the operation. Robotic Telepresence will project these unstructured work sites to the human operator to allow the intelligent, timely decisions required for successful completion of the servicing tasks.

ROBOTIC TELEPRESENCE

In order to gain an appreciation for human-in-the-loop control of robots, an understanding of standard autonomous robot operation is helpful. Figure 2 shows a typical control circuit for an industrial robot. The robot is programmed to do a specific task in a specific environment with specific hardware. As the task proceeds and the robot interacts with the work environment, the robot state and the task state are monitored by the low level controller which provides the robot with feedback control signals based on predefined parameters. When the predefined parameters are exceeded, the system should gracefully shut down. Note that there is no interactive control information feedback to the task programming block once the high level instructions are issued. The low level controller communicates with the task programmer only at predetermined intervals.

One potential control configuration for Robotic Telepresence is shown in Figure 3. This configuration presents the robot/task state information to the human operator who is now aware of the real-time status of the robot/task. This awareness permits real-time changes in the instruction set to the computer which in turn provides the low level control to the robot. The robot/task state information is also fed back to the low level controller to provide control loop stability and to integrate the status with the next set

of operator instructions. The human operator can now "interact" with the work environment to adjust to unanticipated changes in the unstructured workload.

The human has several methods of natural feedback as shown in Figure 4. Robotic Telepresence seeks to use as many of these feedback systems as needed to achieve synergism between human and robot. Visual, audio, tactile, kinematic, proprioceptive, and vestibular sensors are all used by humans to sense environmental information for cognitive processing. Although vision processes are heavily involved in much of the information gathering, the other senses are capable of independently supplying critical data about the interaction between the human and his/her world. In fact, the loss of vision or any other single sense does not render the human totally nonfunctional. Similarly, the manipulation of objects by human hands does not require visual sensory input, but visual information about size and anticipated force/torque requirements certainly enhances object manipulation. Proprioceptive data can be used to gauge size and shape while yielding very little tactile information about the texture and temperature of an object. Audio feedback is another separate channel that can provide specific information about the work site. Smith (personal communication) indicates that operators of the Naval Ocean Systems Center's remotely operated dune buggy found information from the audio channels to be very beneficial relative to feedback about engine loading and as a surveillance method. Robotic Telepresence seeks to exploit these multiple paths of human information collection by sensing information at the robot work site and feeding the information back to the human operator in a manner that is consistent with "normal" direct human perception.

AREAS OF MAJOR WORK

Since the Air Force program in human controlled robots is still in its embroytic stages, the research to develop Robotic Telepresence and synergism between the human and the robot will be initiated in several key areas. The initial focus will be to investigate the applicability and efficiency of feedback mechanisms. The emphasis will be to develop the generic methods to reflect information sensed at the work site back to the human operator at the control room. The goal is to present this sensory signal to the operator in a naturally perceptible manner so that the requirement for human integration of unnatural feedback is minimized. An example of unnatural feedback could be end effector force/torque data displayed as a series of bar graphs which the human must assemble into a mental image of the force/torque vectors. Experiments on feedback mechanisms are planned in the following major areas: (a) vision; (b) fine dexterous manipulations; (c) coarse dexterous manipulations; (d) force reflection mechanisms; (e) tactile sensing and stimulation and (f) auditory localization. While the experiments and developmental research in these areas will include hardware and software development, the focus will center on developing the capability to complete tasks by human remote control of robots.

Since visual observation is a primary human method of interacting with the environment, a high quality visual display system will be one key element in Robotic Telepresence. Present concepts for visual displays include wide-field-of-view, binocular, helmet mounted systems with the ability to project three dimensional imagery from stereo cameras mounted on the robot. Several initial factors must be considered and investigated in the vision concepts. The advantages and/or disadvantages of color vision must be characterized. The effects of stereoscopic vs 2D flat panels must be

evaluated. Eye slew rates and tracking must be quantified and integrated into the display system in order to keep the operator from experiencing tracking delays. These and other factors associated with displaying high quality video information to the human operator must be examined in the development of the Robotic Telepresence visual display system.

Dexterous manipulation is key component in the R/T concept that can be viewed from at least two perspectives: fine manipulation with the hand and gross manipulation with the arms. R/T manipulation research will be initially dichotomized into these two subgroups. Our fine manipulation studies will concentrate on the control of a left-right pair of Utah-MIT Dexterous Hands (Jacobson, 1986) using hand exoskeletons (positional masters) on the operator's hands. An initial area of investigation will examine the number of degrees of freedom (DOF) required to perform various generic and operational manipulation tasks. Since the Utah-MIT Dexterous Hands have the capability of disabling one or more of its 16 individual joints, they can be used to investigate central methods for gripping and to evaluate robotic dexterity requirements. Additional work is planned to investigate two hand operation and manipulation which includes interactive work between the hands (one hand exerting forces and torques on an object while the other hand grasps and steadies the object). The hands have provisions for tactile sensing pads and will be used as the platform for tactile sensors which support tactile stimulation research. Initial coarse manipulation studies will be conducted using a dual-arm 14 DOF exoskeleton controlling two 6 DOF industrial arms. Areas of initial investigation will center on the 14 DOF to 12 DOF mapping of master to slave, the fidelity of control required, motion scaling, and performance requirements.

Force reflection has been shown to aid task performance by reducing task completion time and by reducing total task errors (Draper, 1987). Research in force reflection has been initiated through a project to build a dual-arm anthropomorphic force reflecting exoskeleton. Upon completion of this exoskeletal system, it will be the primary research tool to define and examine the parameters of force reflection for operational tasks, force scaling, and force reflection fidelity requirements.

Tactile sensing is an important R/T component associated with the above mentioned dexterous hands. Tactile sensing is the first half of the challenge of getting work site information back to the human operator. Tactile stimulation of the operator's hands must reflect "tactile sensing" at the robot's hands to complete the tactile feedback loop. Combination of tactile stimulation with hand force reflection will be investigated to identify the central parameters needed to recognize shapes, forms and textures independent of visual input. Although technology exists to build workable tactile stimulators such as the OPTACON (Bliss, 1970), a flexible tactile stimulator that fits in the operator's glove is still being pursued (Terwilliger, 1984; Foley, 1987). While commercial tactile/touch sensors are available from various manufacturers, the flexible, miniaturized tactile sensor arrays required to detect subtle detail at the work site are not yet within the state of the art.

As previously mentioned, the auditory channel provides additional information to the R/T operator. While the role of auditory feedback beyond communication and warning has yet to be completely defined, this feedback mode

will supplement the other human feedback channels to permit more efficient operation of the R/T system. Although current auditory localization research is not directed at R/T (Doll, 1985), progress will be followed closely for potential application.

SIMULATION OPPORTUNITIES

Simulation has a strong role in Robotic Telepresence development. Modeling and simulation requirements range from full system modeling down to individual controller-to-joint simulation.

Since R/T is a human-in-the-loop based control system, direct simulation response of a robotic model to a human operator's positional controller is required. Additional modeling is needed to simulate the robot model's interaction with its work site. This robot-to-work site model could calculate the forces and torques expected due to the interaction. These forces and torques would then be used to drive force reflection actuators mounted on the human's positional hardware. These major simulation tasks would permit a human operator to interactively control a simulated robot in its work site model.

At a lower level, interactive simulations will be used to evaluate and validate design concepts of individual joints of exoskeletons and other force reflecting positional controllers. These simulations and models will be used to test new control strategies, evaluate systems models and define key performance parameters (such as time delay) to guide prototype design and fabrication. From an operational perspective, models of the controller and the robot could be used to "individualize" the human operator's physical characteristics to the generic controller and its associated robot.

SUMMARY

Human-in-the-loop control of robot workers has substantial potential to protect maintenance personnel against exposure to hostile environments. Presently the Air Force Robotic Telepresence Program is investigating the human machine interface required for sensing human position to control the robot and is developing feedback mechanisms to convey work site information back to the human operator in a naturally perceptible manner. Research efforts have been initiated in the areas of force feedback, tactile stimulation and visual feedback mechanisms. Simulation to develop interactive models for human control is also underway. Simulation can effectively reduce development costs while shortening overall research schedules.

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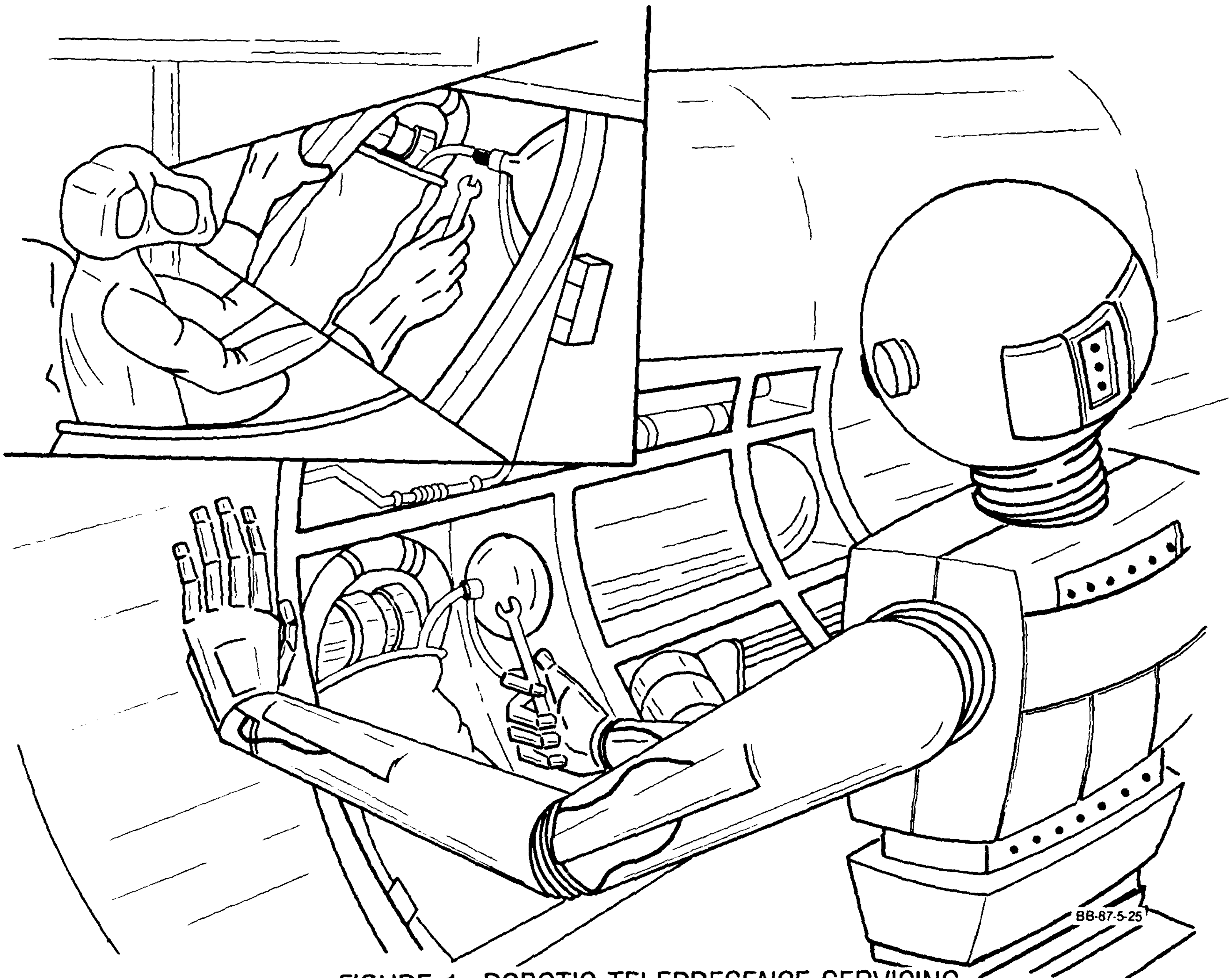

FIGURE 1: ROBOTIC TELEPRESENCE SERVICING

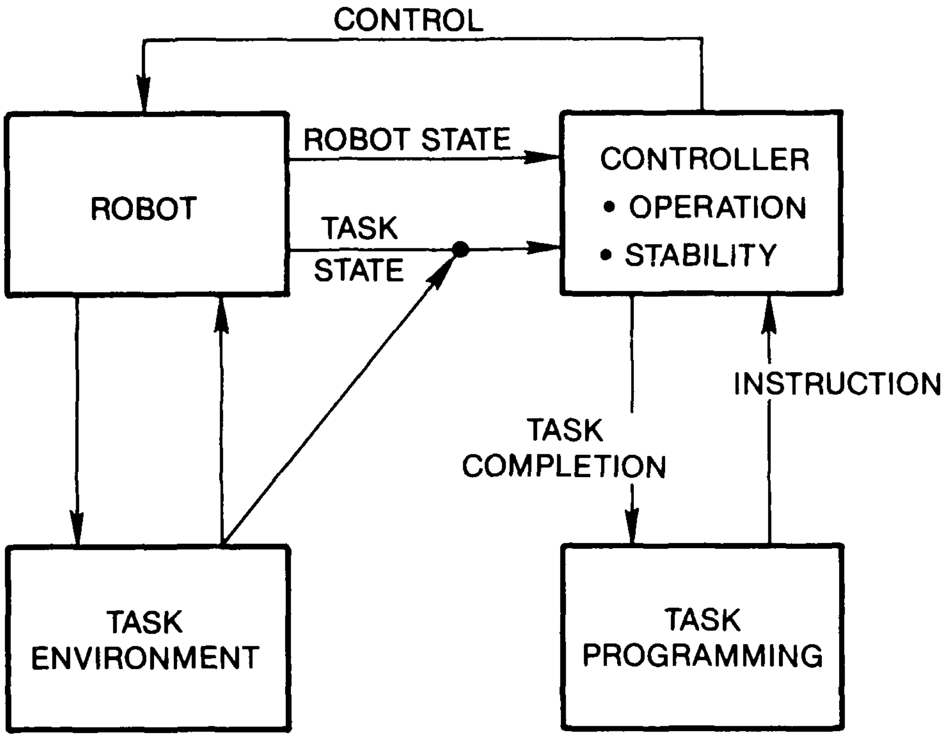

FIGURE 2: INDUSTRIAL ROBOT CONTROL

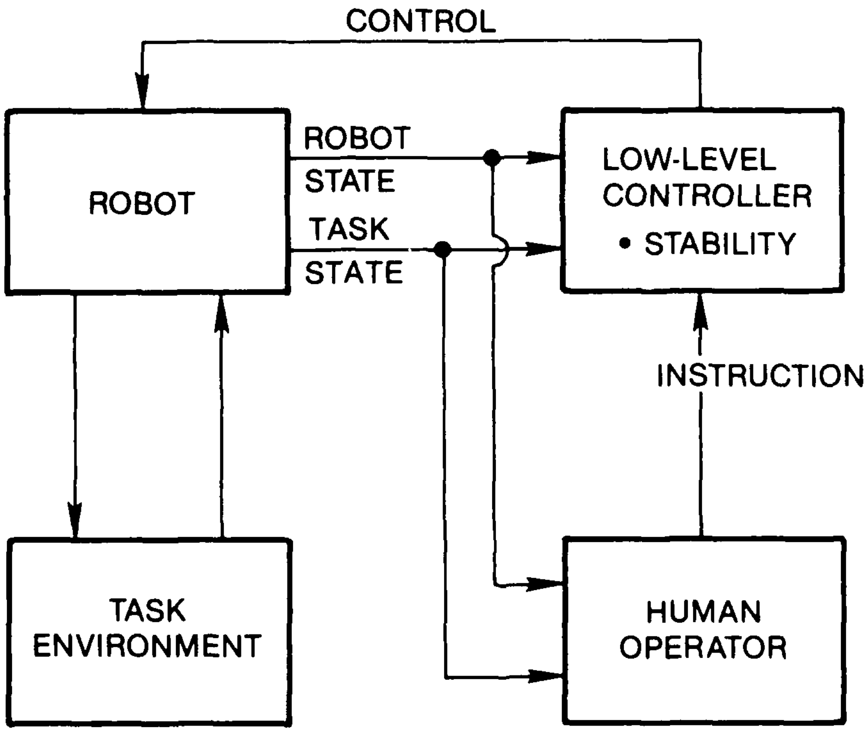

FIGURE 3: HUMAN-IN-THE-LOOP

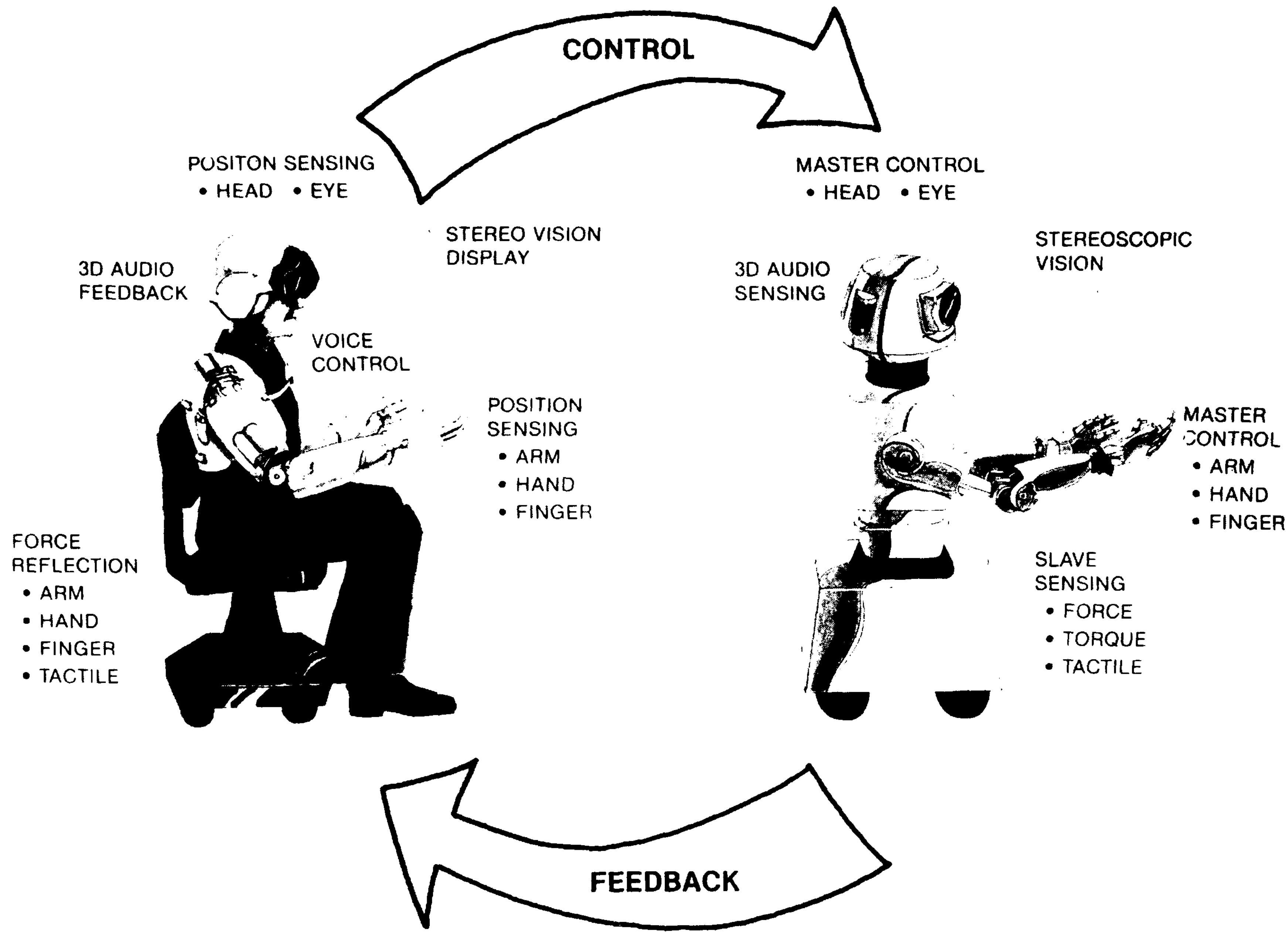

FIGURE 4: HUMAN-MACHINE INTERFACE MODES